SOFTENING THE HABITATS
SUSTAINABLE INNOVATION IN MINIMAL MASS STRUCTURES AND LIGHTWEIGHT ARCHITECTURES

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Building Integrated Photovoltaic (BIPV) applications with ETFE-Films

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Abstract

This paper describes the design and installation of building integrated photovoltaic (BIPV) in combination with transparent structural membranes made of ETFE-films. The contribution refers to three project examples, designed and built between 2010 and 2018.

The first example is about a transparent roof with a total area of about 9,600 sqm, made of ETFE-film cushions, which spans a parking lot of the waste management services in Munich. The flexible translucent PV modules occupy an area of about three thousand sqm. The PV modules are located in the air inflated interior volume of the ETFE-film cushions. This project was finished in the year 2011. The second example shows transparent façade modules made of mechanically pre-tensioned single-layer ETFE-films with organic photovoltaic cells (OPV) and light emitting diodes (LED), applied on the weather-protected backside. An international and interdisciplinary group of researchers has received funding from the European Union's Seventh Framework Program (FP7/2007-2013) [1], to develop the façade modules from 2013 to 2017 in the frame of the project ETFE-MFM (Multifunctional Façade Module). The third and newest example shows transparent façade modules with organic photovoltaic (OPV), glued onto the printed backside of the ETFE film. Aluminum-frames of different sizes carry the pre-tensioned films. The preinstalled modules were mounted and the OPV was connected to the power inverter on site. The modules form the transparent curtain wall of a one-story brick building on the premises of the company MERCK KgaA in Darmstadt. The project was finished at the beginning of the year 2018. It can be assumed, therefore, as the world's first energy-efficient, digitally printed single-layer ETFE curtain wall façade equipped with OPV-elements.

Keywords: building integrated photovoltaic, structural membrane, transparent roof, single-layer ETFE-film, ETFE-film / foil cushion, organic photovoltaic, OPV, light emitting diode, LED, multifunctional façade module.

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1. Introduction

The following three examples show the fast development in the field of photovoltaic and the great potential that lies in the combination of PV-cells, especially organic photovoltaic cells (OPV), with the ETFE-films.

2. Three project-examples of BIPV with ETFE-films

2.1. Project AWM carport, Munich/Germany

In the year 2011 the City of Munich (Germany) got a new membrane roof for their parking lot of the lorries for the waste management services. The reconstruction of the roof was necessary, because the former textile membrane roof collapsed in parts under snow and ice loads a few years before. The client decided for a new 9,600 sqm sized roof, made of a steel structure, covered with 220 air inflated ETFE-film cushions with 2,640 integrated PV-modules. The design from the architects Ackermann & Partners in Munich, presented here, won the competition for this new and innovative membrane roof.

Figure 1:AWM carport-roof, top view

The translucent PV modules with a total surface of about 3,000 sqm, were fixed in a removable way onto the middle layer of the 3-layers cushions by using mechanical fasteners. The PV-modules of amorphous solar cells are enclosed, therefore, by transparent ETFE-films, and kept safe from external exposures, like rain, snow, ice and dust. The outer cushion layer made of a 0.25 mm thin transparent ETFE-film reduced, of course, the solar radiation, needed for the

generation of electric energy by the PV-modules, but the reduction in solar transmission amounts only about 10%. The performance of the photovoltaic plant decreased since installation, although the modules are weather protected and the upper ETFE-film shows no clouding or significant contamination, as expected. Furthermore, the temperature inside the enclosed air space is moderate, because of the continuous air exchange.
This indicates that a few modules are defective and, therefore, affect the overall energy output. Unfortunately, the PV-producer and the used product are not available anymore.

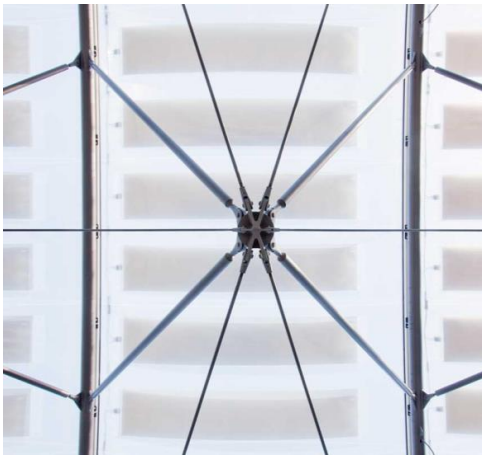
Figure 2:AWM carport-roof, view from below

The lower layer of the 3-layers ETFE-cushions was printed with a dot-pattern, to serve shading and to reduce the thermal impact in summer on the huge open parking lot, the workers and the lorries.

The decision for taking ETFE-film cushions for the cladding of the roof, instead of other materials, like over-head glass panes, was basing on the following advantages:

- low weight of the transparent roof cover
- low weight of the supporting steel structure
- foundation on the existing concrete-foundations of the old roof
- possibility to protect the PV-modules from external exposures
- low expense of work for maintenance and cleaning of the huge-sized smooth ETFE-film surface, because of self-cleaning by rain water
- long durability of the ETFE-film (> 25 years) because of being a fluoropolymer material
- good behavior in case of a fire (ETFE-film are classified as B-s_1,d_0 according to EN 13501-1 / EN 13823 / EN ISO 11925-2, that means self-distinguishing, no burning droplets, low fire propagation, low flammability, melting (self-opening) above a flame / hot gases)
- good recyclability of the clear ETFE-film because being a thermoplastic material (printed ETFE-films cannot be recycled, and must be utilized, therefore, thermally)
- simple replacement of single roof components and easy waste separation of the different materials at the end of the components life time
- clear and nice design vocabulary by the synclastic surfaces of the air inflated cushions
- natural lighting of the garage area and, therefore, minimization of the energy for artificial lighting, because of the high and natural light transmission of the ETFE-film
- low construction costs

For the fixation of the photovoltaic modules onto the middle layer of the ETFE-film cushion mechanical fasteners with slotted holes in the outer edge of the PV-modules were used, to resist deformations from temperature without restraint forces. The upper layer was clamped separately from the other two layers in order to exchange a defect PV module without any problems. This allows an easy access and a quick replacement of a defect module.

This innovative project is a milestone in the development of multilayer ETFE-film structures with integrated photovoltaic. The combination of both components allows the owner to get many benefits, as weather protection, light transmission, the gain of electric energy, and finally, a nice architectural appearance of his innovative building.

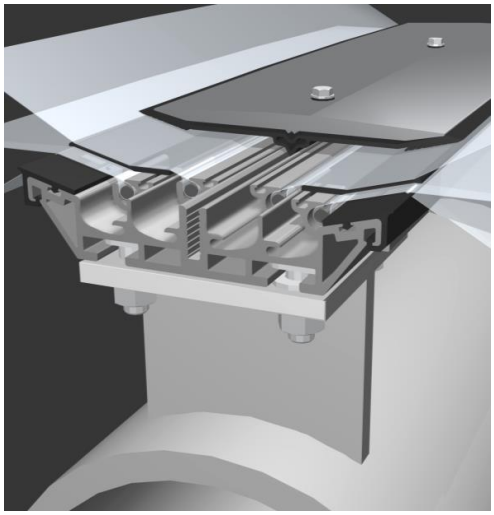

Figure 3:Isometric view of the 4-Keder-clamping system, especially developed for separated upper and lower cushion layers

Table 1: Project Data, AWM carport for the waste management services in Munich, Germany, three layers ETFE-film cushion system with integrated PV-modules, 2011

Project data	
Client	City of Munich
Architects	Ackermann & Partners, Munich
Structural Engineers	Christoph Ackermann, Munich
Membrane Engineering	Konstruct, Rosenheim; Taiyo Europe
Executing Company (GC)	Taiyo Europe, Sauerlach
Supplier (steel structure)	steel concept, Chemnitz
Surface (ETFE-film cushions)	9,600 sqm
Number (ETFE-film cushions)	220
Surface (PV-modules)	3,000 sqm
Number (PV-modules)	2,640
Rated power per module (STC)	57 W

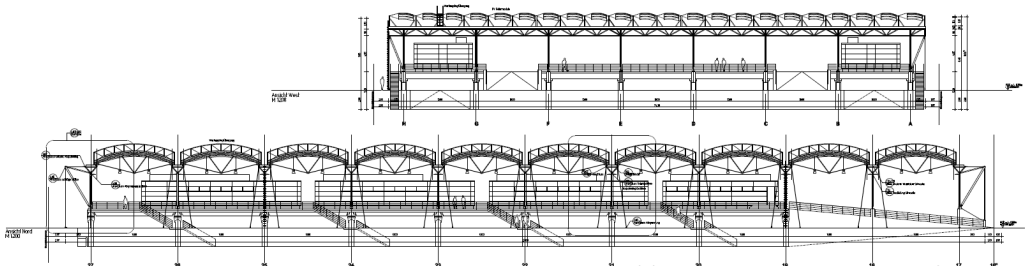

Figure 4:Sections of the building

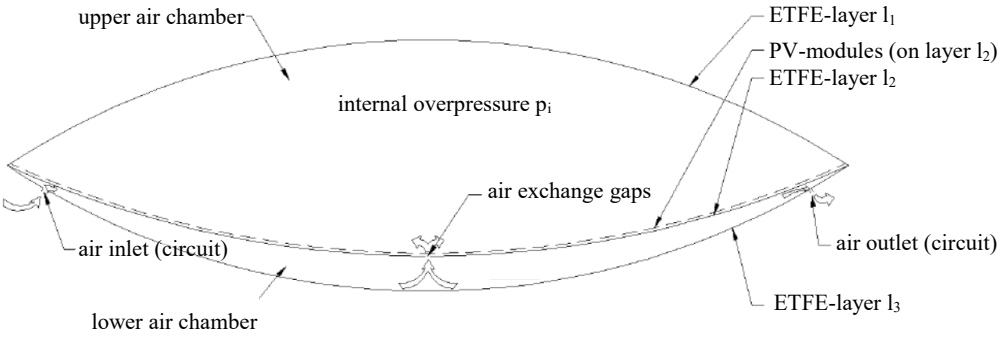

Figure 5:Principle design of the 3-layers ETFE-film cushions

2.2. Project ETFE-MFM, Pamplona/Spain

This chapter summarizes the developments, done in the context of the ETFE-MFM project. It was a research project funded and supported by the European Union Seventh Framework Programme (FP7 / 2007-2013, Grant Agreement no. 322459). The development was done by different project partners, specialized in the technologies, needed for the development of smart façade modules [1].

The project focused on the design, manufacturing and testing of a smart solution for current façade multifunctional requirements in the building sector, like load bearing, lighting, displaying and energy harvesting. The developed system is based on two ETFE-films (front and back film), embedding photovoltaic elements, in this case equipped with organic photovoltaic cells (OPV), but also equipped with light-emitting diodes (LED).

The purpose of this project was to provide a standardized semitransparent façade module acting as flexible LED display, with an electric consumption, supplied by solar energy. In this way, LED strips, organic photovoltaic cells and flexible electronics were laminated between the two ETFE-films by using Ethyl Vinyl Acetate (EVA) as interlayer-material.

The lamination process was optimized in order to provide good optical and mechanical performances without affecting the functionality of the different components.

The resulting multilayer film is held by a 1.5 m x 1.5 m sized aluminum frame, developed especially for such applications. The frame should clamp the multilayer film safely without welded keder-pocket, to prevent the embedded OPV, LED and protruding electric cables from damages at the processes of production and assembly.

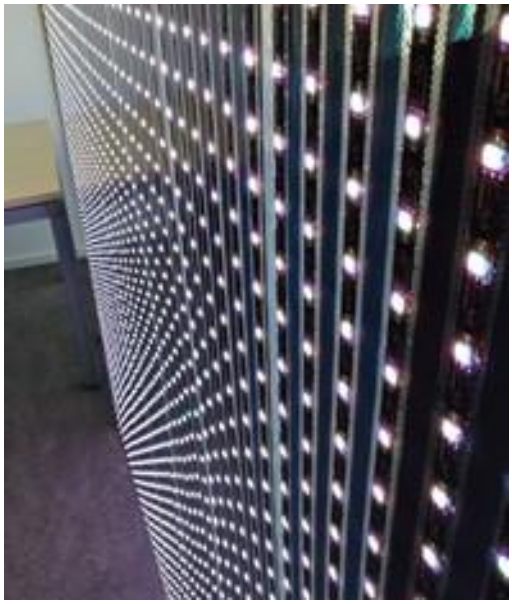

Figure 6: Prototype of the ETFE-MFM module, here with LED switched on (uniform white light) [1]

Four prototypes of this module were installed vertically as a curtain wall of an existing building in Spain, to enable the one-year-lasting monitoring under real conditions. The four modules showed an average electric output of about 43 Wh per day and module and up to 90 Wh in maximum. This energy complies with the energy, needed for a video transmission that is lasting up to 150 minutes, if the consumption of the light emitting diodes is 35 W.

This second example shows another milestone in building with the combination of ETFE-film and photovoltaic, in this case additionally equipped with LED. The applied combination constitutes a trendsetting approach to manufacture many of identical modules, to function as a big energy-efficient façade-display as curtain wall in front of a building.

Table 2: Project Data, Research Project Multifunctional Façade Module (MFM), 2 layers ETFE with embedded OPV and LED

Project data	
Funded (2013 – 2017) by	European Commission
International Research Project Partners	Acciona, Cener, Greenovate, Itma, Opvius, Taiyo Europe
ETFE-membranes / extrusion profile	Taiyo Europe, Sauerlach
OPV	Opvius, Kitzingen
Surface (ETFE)	2.25 sqm (per 1.5m x 1.5m module)
Surface (OPV)	~ 1.75 sqm

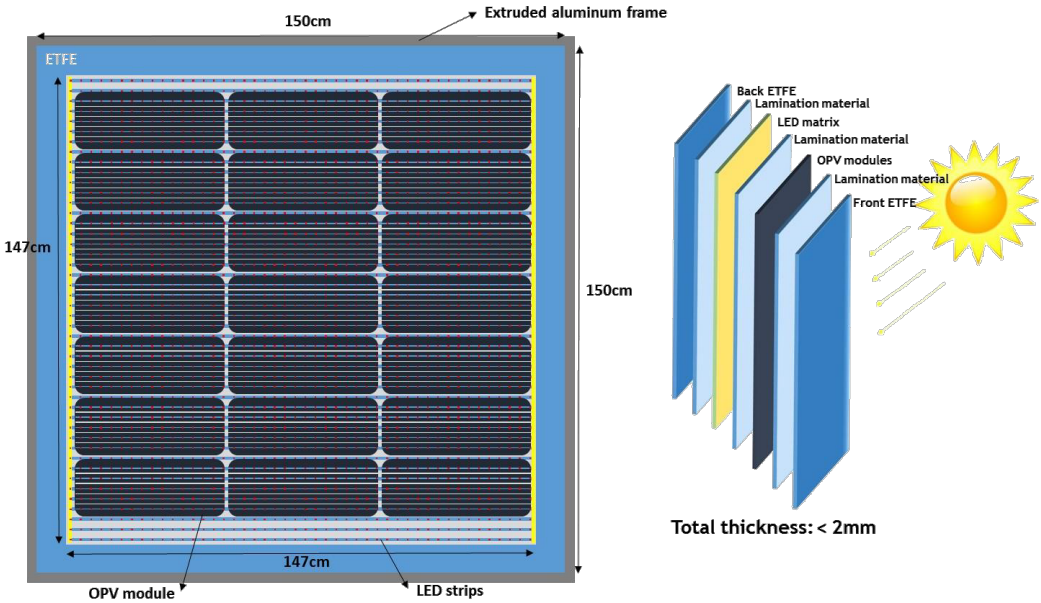

Figure 7:Layer structure of the multifunctional façade-module (ETFE-MFM) [1]

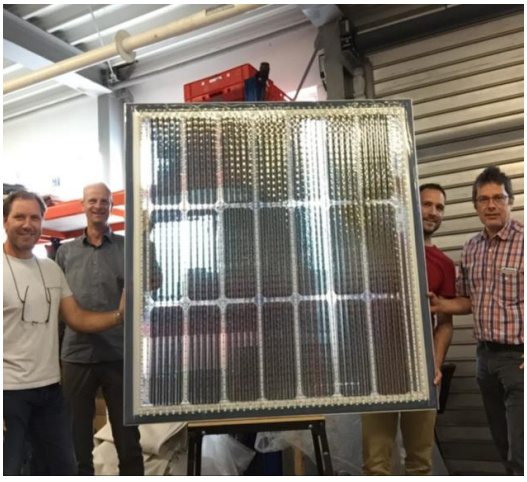

Figure 8: Pre-assembly of the first prototype, Taiyo Europe's workshop in Sauerlach, Germany

Figure 9: Installation of 4 modules of the prototype on ITMA premises in Pamplona, Spain [1]

2.3. Project MERCK Transformer Station, Darmstadt/Germany

The third example also shows a modular design for curtain wall façades, which also consists of the combination of ETFE- film and organic photovoltaic (OPV). Here, three different organic shapes of OPV elements were applied on the mechanically pre-tensioned ETFE film for the first time. The 64 membrane modules with aluminum frames form a curtain wall on the four sides of the existing transformer building on the premises of MERCK in Darmstadt in front of a wall made of fired bricks. The selected colors of the digital printing of the ETFE film follow the corporate identity of the company. Since the relatively small area of the OPV provides only a low power yield. The small façade is, therefore, a pilot project, that should demonstrate the possibilities of this technology. The direction in which this technology goes is clear: the individual design of modular, aesthetically appealing multifunctional curtain wall façades. Topics include lightness, transparency, aesthetics, careful use of resources and solar energy generation. The project uniquely combines aesthetics and multi-functionality. The result is a great architectural work of art with a high innovative demand.

Figure 10:Assembly of the 64 frames in Taiyo Europe's workshop (standard size 4.2 x 1.3 m, as shown here; special size 4.2 x 0.5 m

Table 3: Project Data, transparent ETFE/OPV–façade, MERCK transformer building (B7/B8) in Darmstadt, Germany

Project data	
Client	MERCK KGaA, Darmstadt
Architect	Henn Architects, Berlin
Structural Engineer (curtain wall)	Leicht, Munich
ETFE-membrane/extrusion profile	Taiyo Europe, Sauerlach
OPV	Opvius, Kitzingen
Steelwork	Steelconcept, Chemnitz
Surface ETFE	300 sqm
Number of modular frames	64
Number of PV-modules	1,578 (3 types of organic shapes)

Figure 11:OPV-modules glued on the backside

Figure 12:Connecting the OPV-modules

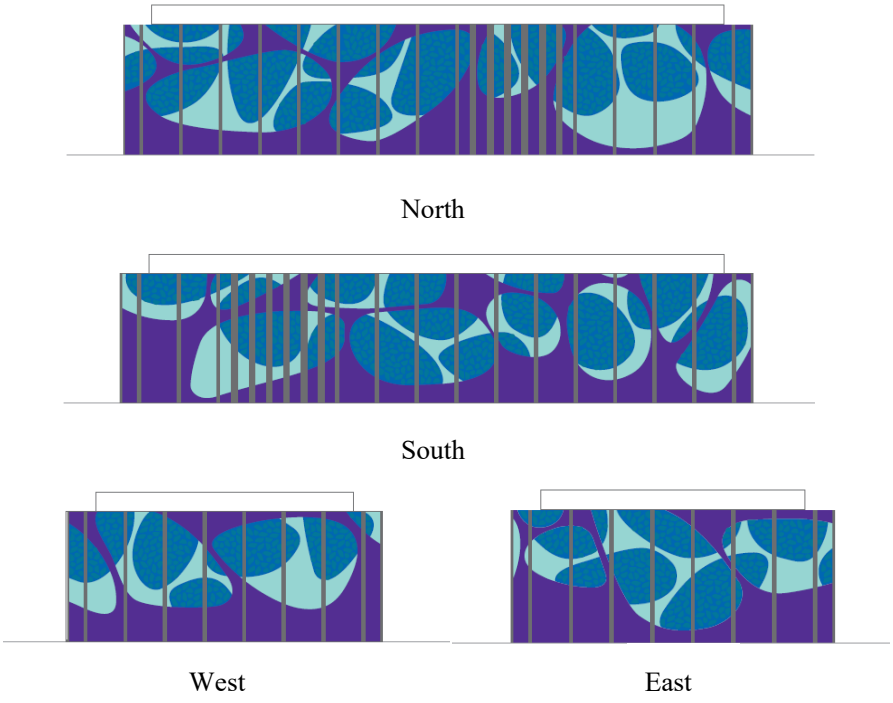

Figure 13:Side views of the building

Figure 14: Installation of the pre-fabricated façade-modules on site

Figure 15: Finished façade (MERCK premises, Darmstadt, Germany)

Figures 16:MERCK Transformer Station, Darmstadt, Germany: appearance of the original brick-façade

Figure 17:MERCK Transformer Station, Darmstadt, Germany: appearance of the new curtain wall

3. Conclusion

The projects presented above show the possibilities of building integration of photovoltaic (BIPV) in combination with transparent ETFE film, but they also show the beginning of a construction method that will only mature to a trend-setting technology after overcoming the teething troubles. However, the combination of PV and ETFE enables, like no other, the realization of modular, individual, multifunctional and aesthetically pleasing façades and roofs. The examples also show that requirements for aesthetics, transparency, lightness, load transfer, weather and fire protection, as well as the careful use of our natural resources and the solar energy production are achievable. Since the examples refer to curtain walls and open spaces, building physical requirements due to thermal insulation were not to consider, here.

Currently the membrane construction sector is changing rapidly to the extent that modular construction with multi-layered structure and multifunctional use is now part of it. Due to their low weight per unit area and their multi-functionality, modular construction also undoubtedly belongs to the field of lightweight structures. Such multifunctional modules are becoming increasingly important for architects and building owners, and, therefore, for the construction industry as well, as they allow very different applications and functional possibilities. However, they also lead to a major challenge for membrane construction companies, architects and structural engineers. This means that suitable production methods with appropriate quality assurance for modular multilayer structures must be present or developed, and the topics of building physics, fire and structural behavior, but also production and assembly technologies of modular multilayer membrane structures are to consider in design and engineering, including all interactions.

Which membrane construction company is capable of producing a large number of uniform or even different modules economically and in terms of a needed high quality? Which structural engineer is also a specialist in building physics or photovoltaic and knows the elements stress-strain behavior or its structural limits? Which architect can claim that he masters all relevant topics in such a way that he can present a harmonious execution planning of such modular constructions without involvement of experts in the early phase of the planning process already? The knowledge of all the elementary properties and requirements, but also their interactions, will increasingly determine the success of such modular membrane projects as well as the future of the planners and specialist companies involved in this new technology.

4. Referencing literature

[1] A. Menéndez, A. Martínez, A.Santos, B. Ruiz, K. Moritz, I. Klein, J. Díaz, A.R. Lagunas, T. Sauermann, D. Gomez, “A multifunctional ETFE module for sustainable façade lighting: Design, manufacturing and monitoring”, *Energy and Buildings*, *Elsevier*, vol. 161 (2018) 10-21